Semiconductor Optoelectronics
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Lecture – 35
Semiconductor Laser-III Single Frequency Lasers

We continue our discussion about various laser structures and today we will discuss about single frequency lasers. Single frequency lasers refer to semiconductor which oscillate in a single longitudinal mode and a single transverse mode.

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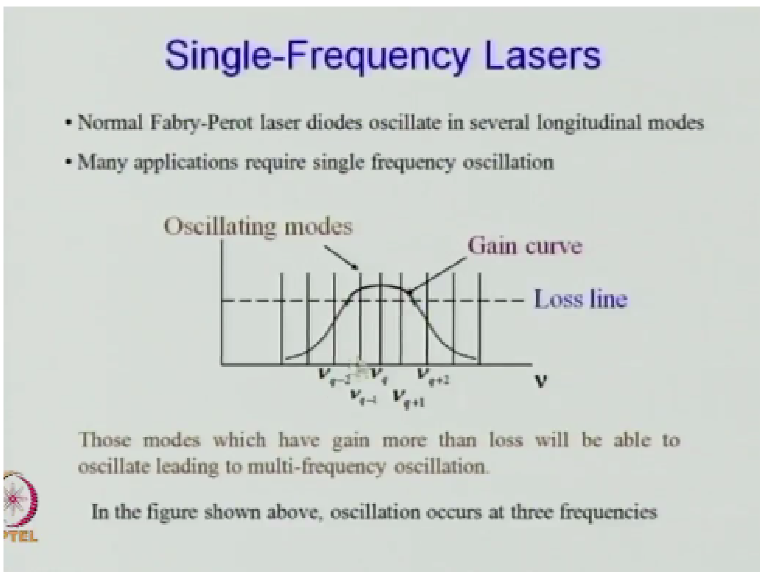

The basic idea of single frequency lasers is illustrated here. We have discussed this but let me recall it that normally Fabry-Perot laser diodes of oscillate in several longitudinal modes. Because you can see here that this is the gain curve and this is the loss line and those frequencies, the vertical lines represent the resonance frequency allowed by the resonator but only those frequencies here 1, 2, 3; at those frequencies, gain is more than loss.

Loss line is here horizontal line, gain is more than loss and therefore only these 3 resonance frequencies or these 3 longitudinal modes can oscillate in a laser. So, normally all longitudinal modes or all resonance frequencies allowed by the resonator for which gain is more than loss will oscillate. Which means generally we have few modes oscillating in a semiconductor laser.

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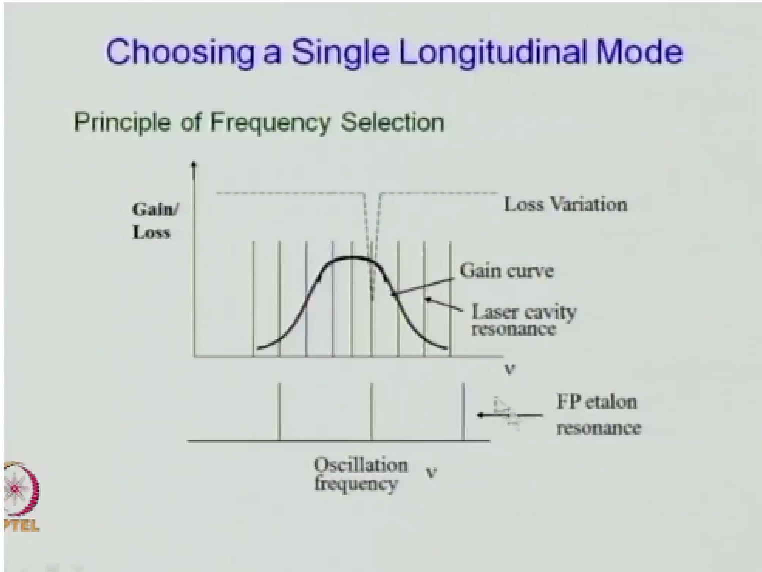

If you can somehow increase the loss for all modes but one more which you want to lace, then it is possible to choose only one longitudinal mode. So, the idea is here again. The gain curve is the same. The resonance frequencies are the same but if you can have a loss profile where loss is more for all frequencies but for one, here. Then, it is possible that only one of these longitudinal modes will oscillate. For example, we will see the mechanism of choosing single frequency lasers but if you have Fabry-Perot etalon.

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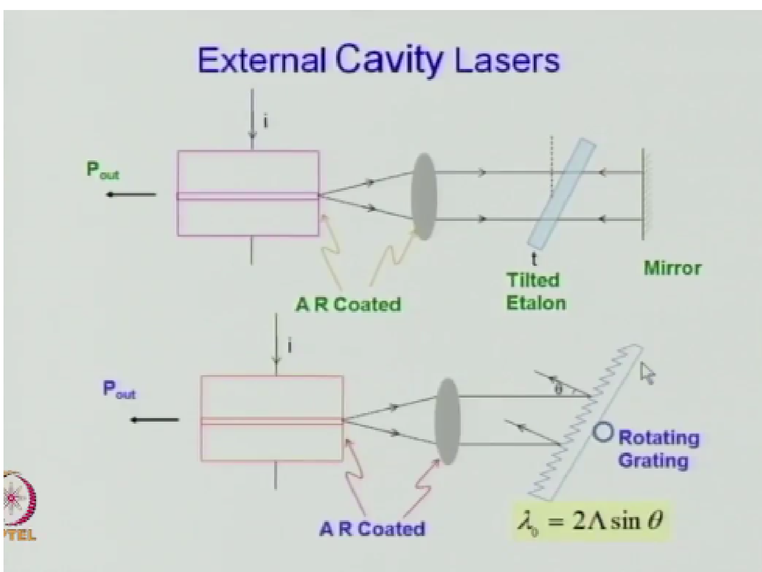

Let me show the next diagram and then come back. So, this is the laser here. It is AR coated (antireflection coated) here and the light output from this end passes through this. So, this is the semiconductor laser, the basic device. Current passes through the device and gain is provided by this medium and there is a Fabry-Perot etalon, tilted etalon. We have discussed how the tilted etalon chooses a particular required frequency.

So, this is a tinted etalon in the cavity. So, the cavity comprises of this mirror and the mirror at this end. The cleaved end at this end which is not antireflection coated and this mirror which is usually 100% reflecting that is the one which cavity. So, this is the cavity, from here right up to this. So, this is the way light is going back and forth. But there is an etalon in between that provides only certain resonance frequencies to pass through. The transmission of this etalon if I may use the bore.

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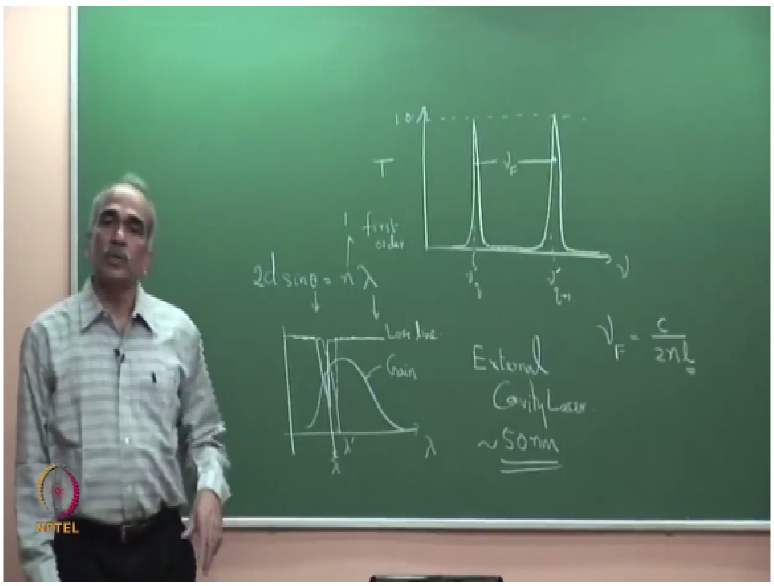

If you see the transmission of the etalon. So, this is frequency (()) (04:00), then the transmission shows peaks like this, narrow. So, what I have plotted is the transmission of the etalon. So, this is transmission and this is one. So, one point, transmissivity or transmission, what is the frequency. So, there are frequencies here, mu q and mu q+1, this is of the resonator, so let me put them as dot. This is of the etalon, not of the resonator.

So, there are transmission peaks here which means a frequency which is here will pass through the etalon as if the etalon is not there. So, this etalon here, that frequency will pass through as if the etalon is not there, which means for these resonance frequencies this cavity is a low loss cavity. Whereas for any other frequency, the etalon transmission is very small which means that is not act as a good cavity and this is the idea by which you chose.

So, let me go back to the figure again hear. You see the etalon resonance frequencies are these. These are the etalon resonance frequencies, separated by a free spectral range which is large because the free spectral range here if you may recall is given by C/2n*l where l is the length of the cavity. For the etalon, l is very small and therefore the free spectral range or separation between the resonance frequencies in large but for the laser cavity, the laser cavity comprises of this whole cavity, let me show again here.

So, this is the laser cavity from here to here. This l is very large and therefore the resonance frequencies permitted by this cavity are much closely placed or the free spectral range for this whole laser cavity is much smaller and therefore let me go back again to the other figure, here. So, these vertical lines correspond to the laser cavity and these vertical lines corresponds to the resonance frequencies of the etalon.

Whenever the etalon resonance frequency coincides with the laser cavity resonance frequency, that particular frequency will pass freely inside the cavity, that is if this happens to be coinciding with the allowed resonant frequency of the laser cavity, then this frequency transmission is one which means it does not see the etalon at all. It is low loss. Etalon is a low- loss device for this frequency. Inside the cavity, there is an etalon which is a high-loss device for any frequency which is here, because it is not allowing those frequencies to pass through.

So, what happens to those frequencies. Those frequencies which are incident here will get reflected in this direction. It is a tilted etalon, the tilt has 2 reasons. Why do we need tilted etalon. One, the frequencies which are not transmitting will get reflected and when it gets reflected, it will go like this at an angle, so it does not go back. The second reason why you use a tilted etalon is by changing this angle theta, you can change the separation mu F.

So, mu F is the frequency separation. So, this frequency separation can be tuned so that at least one resonance frequency coincides with the resonance frequency of the laser cavity. So, at least one resonance frequency, this one or this one coincides with a laser resonance here, so that particular frequency loss is very low. For all other frequencies here, the loss is very high. So, this frequency here sees a low-loss because that is the transmission resonance of the etalon.

So, this is the principle by which it is the same laser structure but the cavity is now (()) (08:22) for all frequencies but for one. Therefore, only the loss curve here (()) (08:28) for one particular frequency which means (()) (08:32) is low. So, gain is higher than the loss and therefore this is the frequency which will oscillate in this place. By this means, we have chosen one single longitudinal mode. Thus, laser structure here, this is an external cavity laser.

So, external cavity laser which means this is the cavity which is coupled to the laser and therefore by using this etalon, you can force the laser to oscillate only in one frequency corresponding to the resonance of the etalon. So, this is one of the widely used a technique called external cavity laser. There are other means by which you get single frequency. The second one which is shown here is a grating.

So, there is no cavity here, so this is antireflection coated. This end is the cleaved end which has 32% reflectivity. So, light which is going back and forth, this is a rotating grating. By rotating the grating, you can make only one wavelength which is reflected back. You see, this is a grating. So, if you have a spectrum. As you know for the grating, if you have d sin theta=n lambda. So, lambdas will have different theta. It is a reflection grating, there are transmission type of gratings and reflection type of gratings, so this is a reflection grating.

In a reflection grating, different wavelengths correspond to different theta. In general, a theta would get reflected like this which means it will not go back to this but only one particular incident angle will go back into this poor and therefore only one wavelength will satisfy this condition of going back. So, by rotating the grating, you can choose different wavelengths to lace in this cavity or at a given angle, there is only one wavelength.

Please see, if you see the gain curve. So, this is lambda or frequency whatever, the gain curve is like this. If you chose the grating, so that at one lambda theta is such that light goes back, so it could be here for example. So, for that loss will be very low. Principal is the same. For all other wavelengths, loss will be very high. So, this is loss line, this is the gain curve. One wavelength lambda here which satisfies this condition where the wavelength is reflected back into the cavity will have very low loss.

For all other wavelengths, the light which is reflected here, those wavelengths which are reflected are at an angle, so they do not go back exactly hear. They may hit here; they may hit here or they may just go out. So, there is no feedback. It is highly loss cavity for other wavelengths. So, this is the way that you can choose any particular wavelength and force the laser to oscillate in a single longitudinal mode.

This is also the principal for tunable laser, external cavity lasers. There are tunable lasers which based on external cavity structure. You can tune 50 nanometres. The losing wavelengths can be tuned of the order of 50 nanometres by using external cavity lasers where you use a rotating grating here. The grating is rotated by Piezo control by current. It is not manually rotated.

It is with high precision you can control the feedback and therefore the wavelengths which you want to chose, one can use the stepper motors here to rotate this and you can choose the wavelengths in steps or you can continuously choose the wavelengths which you to release. In other words, what you are doing by rotating the grating is, now this is the curve for a particular angle.

At a latter angle, so let me draw this with a dotted line, the curve could be like this which means at a different position, this is a lambda dash, this is lambda for which initially, there was low loss but by rotating I have shifted the curve. The wavelength for which you have low loss is this one and therefore only this wavelength will lace, which is the principle of external cavity tunable lasers based on external cavity rotating grating. The grating condition is given here.

This is actually 2d sin theta=n lambda. So, these replaced by the period here grating period 2d sin theta=n lambda, n is order 1, therefore n is not written. For the first order, it is n=1, one can use higher orders also, okay.

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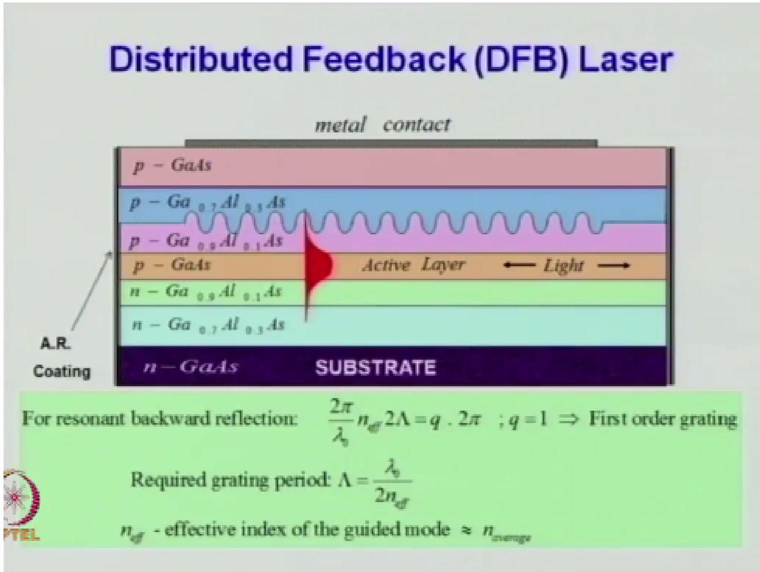

So, let me go to the extension of the external rotating grating. What the grating was doing is one particular wavelength had high reflection going back into the cavity. So, here is a structure which is called the distributed feedback laser. First of all, it is the feedback is distributed all along the length, that is by the name distributed feedback laser. Please see the laser structure, the 2 ends are antireflection coated (AR coated). The 2 ends are antireflection coated which means there is no cavity as such.

However, this structure supports (()) (15:17) like all other double (()) (15:19) structure lasers, it supports a guided mode. In the case of a distributed feedback structure, there is a grating which is a corrugated grating, a periodic structure in the (()) (15:32). The mode which is propagating in this direction continuously sees reflections at these corrugations by this periodic structure. The mode which is going in this direction gets reflected continuously and therefore the feedback is distributed all along the length. Hence the name distributed feedback plays.

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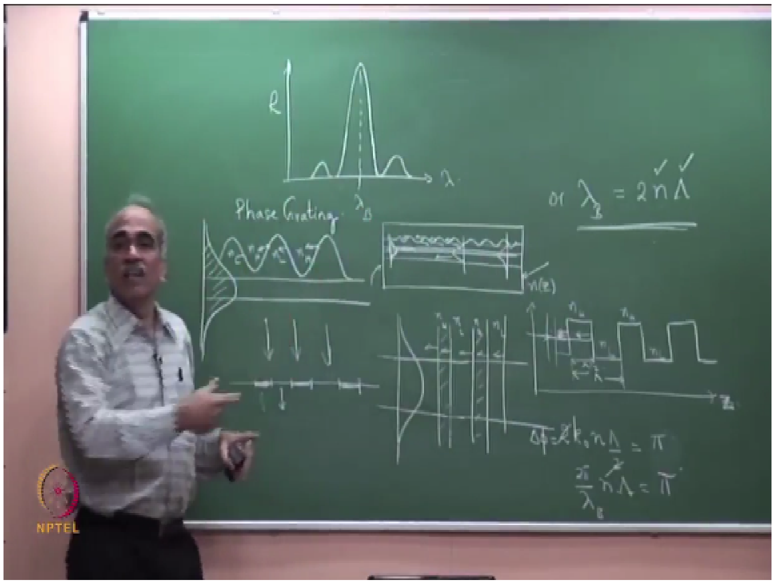

Let me explain this a little bit more on the board. Distributed feedback lasers. These are of course fixed frequency laser, not like external rotating grating lasers. You can tune them. You can rotate the grating and make different angles correspond to different wavelengths which get highly reflected, but in the case of distributed feedback laser, they are fixed wavelength lasers with a little bit of tenability possible. So, let me draw it on the board here.

Okay, let me show the cladding (()) (16:53). So, this is the active layer and there is a mode which is (()) (17:00) because this is a waveguide. Recall that this is high band gap region which means low index, low index and high index. So, this forms an optical waveguide. So, it supports a mode which goes back and forth. If you (()) (17:16) this mode. This mode is let me show is like this. Many of you have studied fibre Bragg gratings where there is a grating which is in the core of the fibre.

So, if you have a periodic structure. Let us say there is a periodic refractive index variation in this direction. So, this is a periodic refractive index variation. There is a guided mode which is propagating but it encounters a periodic refractive index variation. So, n high, n low, modulated n high, n low. It is having a periodic reflection. So, the mode is undergoing periodic reflection at the interfaces like this. The mode is continuously undergoing periodic reflections as it travels in this direction which means it is getting reflected at interfaces continuously, For simplicity, I will show this as a stat variation. So, let me show the refractive index variation like this, step variation and here is the light. Mode or plane wave, you can look at plane wave also going like this. It is the same principle as interference filter, high reflecting coating, multilayered coating is the same principle. So, if the wave is propagating like this, so this is n high, this is n low, n high, n low.

What I have plotted refractive index n versus x, if x is the propagation direction z, so let me put z, n of z, okay. So, high index, low index, high index, low index and so on. So, if you see plane waves ray, you look at the ray picture for simplicity. A ray is reflected from here at this interface, this propagates here and this also gets reflected here. The reflected wave comes back and both of them join here. Now, the ray will get resonantly reflected.

Let me call this as lambda, wavelength, lambda and this is half the way, lambda/2. So, this ray or this way which gets reflected and comes back, if it adds in face with the way which is reflected here then there will be coherent addition and you get reflection, high reflection for those wavelengths which means wave, k0*n refractive index*the thickness lambda/2 round trip, therefore 2 times lambda/2. Please see, this is the path length and phase, phase difference of the wave between this and one which has been reflected from here, so this is delta phi.

But you remember that if this is high index and this low index, there is an additional phase change of pi here but there is no phase change of pi here and therefore if this difference happens to be an integral multiple of pi, that is odd integral or if I take the first order, then if this is = pi, then I will have a resonant reflection.

Please see the wave which is coming back from here, we will add in phase with the wave which is reflected here if this condition is satisfied, 2 times round-trip phase that is why 2 times, phase constant*refractory index of the medium*the distance=pi, that is the alpha. So, what does this give you. This gives you, this goes off and we have 2 pi here, one pi goes there and therefore this is 2 pi, okay let me write, 2pi/lambda B*n*lambda=pi or lambda B.

Lambda B is that wavelength. So, lambda B=2*n*lambda. If you take a period lambda and the refractive index of the medium n, then this wavelength will get resonantly reflected. No other wavelengths will get added in phase, so they will get transmitted. So, if you see the reflection spectrum of such a structure, you will see that, there are side lobe because of 4ier components of the step-like variation. So, this will be the wavelength lambda B.

So, what I have plotted here is reflection R versus wavelength lambda. This is the basic idea behind operation of Bragg grating. It is the same which you see in fibre Bragg gratings also where the grating is written right into the core. In the case of a semiconductor lasers, you could have written waiting in the core, but you do not try to write grating in the core because any fabrication step which introduces some variation here will also introduce defects in the active region and the active region or generation of light is highly sensitive to defects.

We always wanted different density to be as minimum as possible, otherwise non-radiated recombinations will take place and the light generation will go down; and therefore, instead of writing across the 4 waveguide, make corrugations or periodic refractive index variation in the cladding. That is why you see that structure which you saw on the PPT there, that you have periodic refractive index variation here because the materials are different.

Please see this material is different, this material is different here and therefore the refractive index here is different, refractive index here is different and the mode here. Please see, this is the guided mode, the tail of the mode sees this periodic structure. Mode is one field distribution. If you perturb it anywhere, the whole field distribution will get perturb. Even if the tail sees this periodic structure, the entire field will see the periodic structure and therefore the periodic reflection which takes place from here is seen by the entire mode.

In other words, as the mode propagates, there is continuous reflection which is coming like this, backward reflection, as the mode is propagating because what I have shown here is the material structure but if you see refractive index variation that will also be the same. The refractive index here is different n high, this is n low, n low, n high, this is what you see.

What is this, the tail of the mode, so this is the mode. I have zoomed the same structure a little bit more like this and you see the periodic tail of the mode or the evanescent field here sees this periodic structure as it propagates and it continuously suffers reflection. Why this suffer reflection because it sees interference. The condition in this case is that the phase difference between identical phase points here.

This is one wavelength, this is a phase grating, a grating is a structure where there is either refractive index variation or transmission variation. The normal gratings that we see are called amplitude gratings. You are familiar with the gratings where you make corrugations by a diamond-edged blade and then you have a grating structure. So, what do you get. You get a structure where there is opaque, there is transmitting.

So, this is opaque where you have derived it, this is transmitting, this is opaque, this is transmitting, this is opaque. This is the normal diffraction grating that we are familiar in light experiments. It is opaque, transmitting, opaque, transmitting, means what. There is no transmission from here but there is full transmission from here. This is the diffraction grating but this is the amplitude grating.

Whereas here this is called a phase grating. There is no opaque or transmission but refractive indices are different and these are called phase grating. So, a distributed feedback laser has a phase grating in the cladding region. 2 points, why in the cladding because the fabrication process should not introduce defects if there are effects in the active region here core, it will be detrimental to the performance of the source. Therefore, it is corrugated in the clad.

Second, the periodic structure gives continuous feedback all along the length. There is no reflection. These ends are antireflection coated, so that there is no reflection coming from here. Reflection is only by these but this being a periodic structure, the reflection is wavelength selective. The reflection is wavelength selective which means only one particular wavelength which satisfies the Bragg condition will get resonantly reflected as the mode goes in this direction.

Similarly, when the mode comes back, you see it is continuously getting reflected, means it is generating the backward propagating mode. The backward propagating mode as it continuously propagates in this direction. This is the backward propagating mode; it gets continuously reflected like this in this direction. So, when the mode is coming in this direction, it is continuously getting reflected to the other side whereas when it is travelling from this side, it is continuously getting reflected.

But the reflection is not at the ends but distributed all along the length, hence the name distributed feedback. Reflection is a feedback in the case of laser and reflection is distributed all along the length, hence the name distributed feedback lasers.

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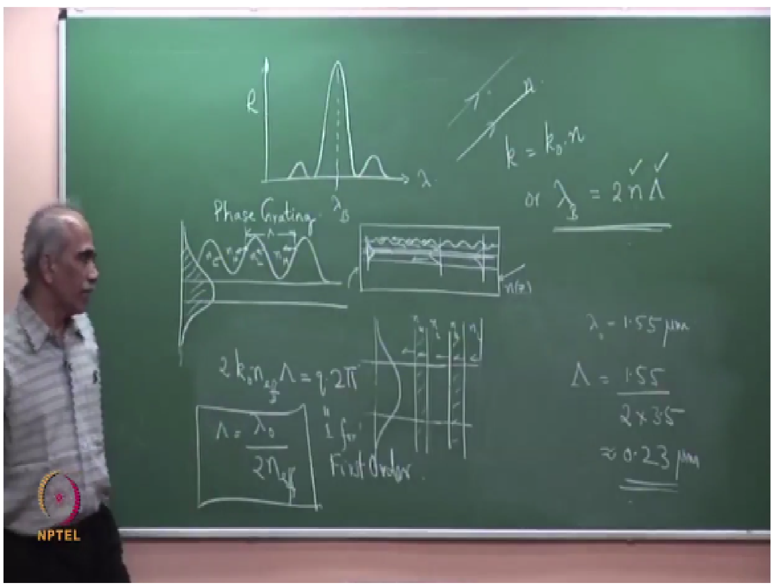

So, in a periodic structure, the condition is written like this. So, these are the 2 phase points, identical phase points and this is lambda, so you can show that 2 times k knot*n effective. Now, n effective because effective index of the mode k knot*n effective, it is not a plane wave. A plane wave if there is a refractive index n and a plane wave is travelling like this, then its k=k0 3 space with number*refractive index.

But a mode is characterised by a propagation constant beta which is = k0*n effective index of the mode which lies between the refractive index of this medium and this medium, alright. So, this into lambda will be = q times 2pi. This is the resonance condition where q is the order. If you are taking first order grating, then q=1 for first order grating. If you simplify this, how did I write this that a round-trip phase within one period is an integral multiple of 2pi, general condition for resonance.

Round-trip phase is an integral multiple (()) (30:40). Round-trip phase is twice wavelength into phase constant, k0*n effective. Is it k, pace constant multiplied by the distance in one round trip to lambda must be = integral multiple of 2pi. There is nothing to remember. This is just the concepts remembered and you get that lambda here is = lambda 0/2n. So, this is the Bragg wavelength.

Only, if you chose a period lambda for the corrugation here, only this wavelength will suffer maximum reflection and therefore the loss will be much less for that. All other wavelengths will simply get transmitted out. These ends are antireflection coated, so there is no reflection coming back. All other wavelengths will simply go out which means there is no feedback. Feedback is for only wavelength. What kind of numbers that we have? what kind of period that you have?

So, if you substitute some number, let us say in optical communication, you want to use at 1.55. So, let us say lambda 0 that you want laser to oscillate at 1.55. You want to make a source distributed feedback for 1.55 micrometre, then you will have to use lambda=1.55/2n effective, normal effective is approximately 3.5. Why 3.5 because the active medium may be 3.6, outside medium may be 3.4.

These are typical number for semiconductors refractive index is 3.5 and therefore n effective you have chosen as 3.5. So, this is approximately 0.23. So, that is the period that is required, the corrugation that is required to be made in the clad. This is a distributed feedback laser. All for these conditions are here in the slide. You can see k knot*n effective*2 lambda=q*2pi, q=1 for first order grating. These are all given in the slide. N effective is the effective index of the mode.

So, all communication sources used for optical communication are distributed feedback lasers. Why we use distributed feedback lasers because we want a narrow linewidth for the laser. As we discussed in the last class, if you use a narrow linewidth source, the dispersion will be much less and therefore you need a narrow linewidth source or a single frequency laser. So, the distributed feedback laser is a single frequency laser.

There are some intricacies here, more details and related to distributed feedback laser. I have talked about the basic principles actually, although this is the wavelength that I have written. When you make a distributed feedback laser, if it is perfectly symmetric, then it will oscillate in 2 modes which are adjacent and there are techniques to suppress such modes.

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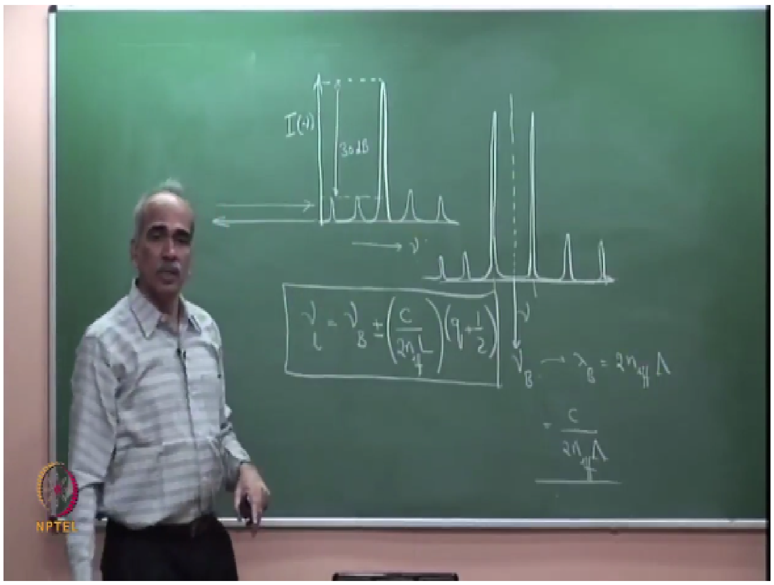

If you see the actual spectrum of a distributed feedback laser, if you see this is nu versus distributed, then if this was nu B, the Bragg frequency corresponding to lambda B, so lambda B=2*n effective*lambda. So, nu B is C/lambda. So, nu B=C/twice n effective*lambda. This is the Bragg wavelength. But actually you see that there are 2 modes. If you see a practical structure which has some more side modes here, side lobes and there is an important parameter, we will discuss. I will not go into the details of this but this is slightly shifted.

The frequency nu of the laser is given by nu B plus minus 1/2=q+1/2 into the free spectral range. The free spectral range is C/2 n effective*l here*q+1/2. Let us say q=1. If q=0 it is the central one here. So, q=0 will have 2 values plus or minus. So, you will have 2 modes, instead of one at nu B, this is the value corresponding to nu B, please see this.

We thought that by taking a grating, we will get one particular frequency nu B, but actually because of the coupling between the forward propagating wave and the backward propagating wave, a coupled mode analysis will show you that it will support 2 modes. The modes are given by this expression, which means even if you put q=0, then you have nu B plus minus 1/2 times this. So, this is the expression which means there are further modes which are separated like this.

This can be explained only by coupled mode theory, but it is possible to suppress this and make the laser to oscillate in the central mode and of course the side lobes will always be there. Side lobes are there because the structure is not perfectly sinusoid. So, you will always get side lobes. In a perfectly sinusoidal structure, the 4ier component will be at one frequency. But if you take a step or if you take any other, you always get the 4ier components at the harmonic frequencies and that is why you get the side lobes.

There is a parameter, normally these lasers oscillate like this. These are called side modes. This is the required mode, so what I have plotted is the power, let us say I of lambda versus nu frequency. The laser output if you see. I said that these are single frequency lasers. It is oscillating in one frequency but actual practical devices will also have side modes coming here, but the power in these is much smaller compared to the power here.

The power here is typically 30 dB down, 30 dB means 1000 times smaller compared to the central load, typically and this is characterised by a parameter.

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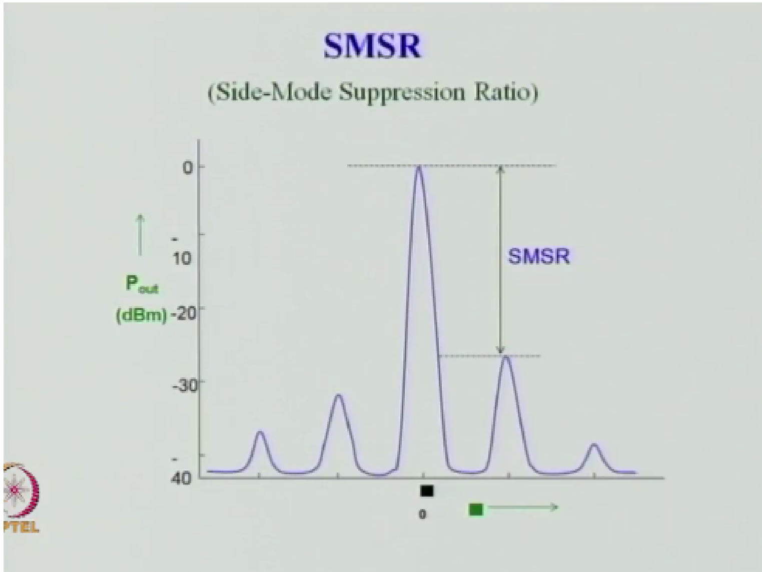

We have I think I have shown here, side mode suppression ratio. So, these are the side mode suppression ratio. When you buy a DFB laser, there is always this specification will be given, side mode suppression ratio. So, side mode suppression ratio or SMSR refers to the difference in power here in dB between the required central mode that particular frequency and unwanted side modes which come because of the periodic nature of the grating. So, this is the parameter typically 25-30 bB or (()) (40:03) SMSR.

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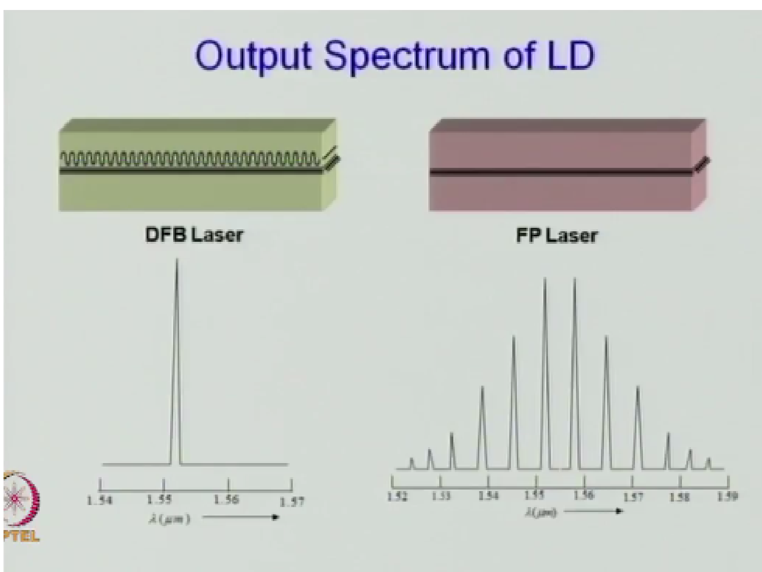

Alright, let me go back to the DFB laser here. So, this is the structure and here is the spectrum just to illustrate. If you take a Fabry Perot laser is the same laser, you have the laser oscillating in multi-longitudinal modes and if you have a periodic grating here in the cladding to make it a distributed feedback laser, it oscillates in a single longitudinal mode. Normally, if you keep the linear scale, you will not see these. This is (()) (40:42) dB 1000 times smaller.

Only if you keep log scale you will see these. In the spectrum analyser, if you choose the log scale then only you will be able to see these. Otherwise, the power here is 1000 times smaller. So, in a linear scale it will be just not there. That is why here I have not shown any of this that actually there is a small amount. This is an illustration showing that it picks up one single longitudinal mode. So, DFB laser is a single frequency laser, alright.

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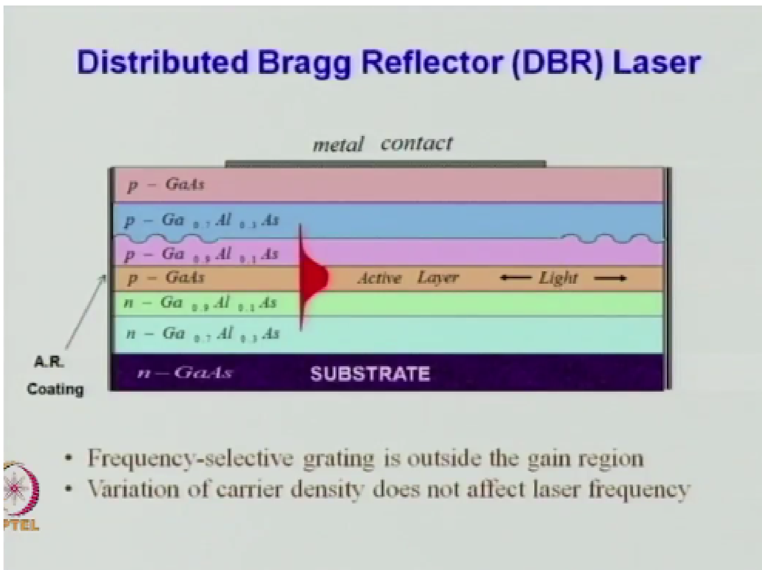

We go to the extension that is distributed Bragg reflector laser. This is not distributed feedback but distributed Bragg reflector. What is the difference here? You can see the structure that there is a difference in the structure between DFB and DBR. I will not go into the details of this couple mode analysis but those of you are interested, you can see the references.

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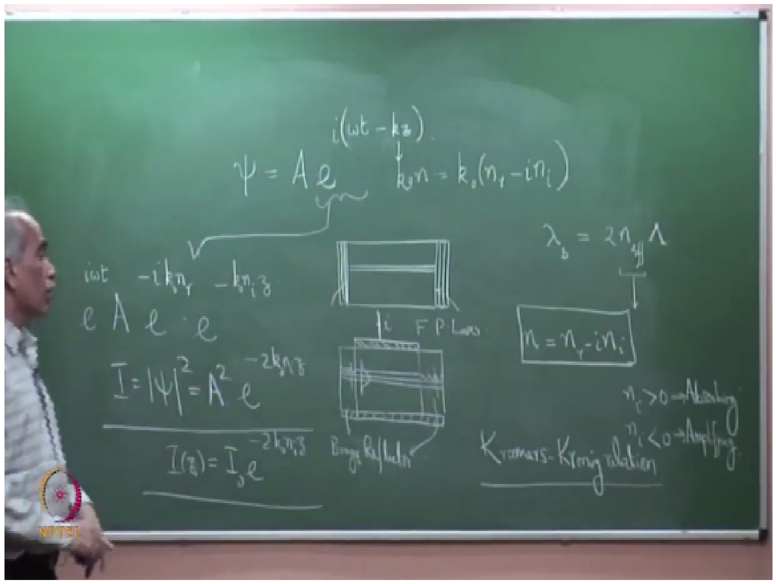

Recall the Fabry Perot laser, the Fabry Perot laser has reflection coming from the 2 ends, the Fabry Perot. So, these are the cleaved facets. Because it is a cleaved facet, it is normally not frequency sensitive, almost all frequencies will get reflected because it is a mirror basically. But instead of this broadband mirror, broadband mirror means mirror which has reflectivity over a wide frequency range. If you use a frequency selective mirror here like the interference filter. If you a frequency selective mirror or high reflection coatings.

For example, here if you put a periodic structure n high, n low, n high, n low and make a high reflection coating here, then that coating will be frequency selective. It will be highly reflecting only at one particular table. So, this is a possibility but in practice, it is not a practical solution considering the fabrication process. So, instead of this, if you have the Bragg reflector. So, this is the structure here.

If you have the periodic reflector which we had all along the length in the case of DFB only at the ends, we do not have anything here and here again we have the periodic structure. So, the mode is travelling like this back and forth. At the ends, if there is a frequency selective grating here, it is not a separate bulk layer but it is within this. This can be must easily fabricated by lithography. This is not by lithography.

It is easy to show here but in a practical situation taking the wafer like this and depositing interference layer is very cumbersome process; and therefore, this is monolithic process, that is on the surface you can do this lithography, lithography and epitaxy, that is etching and re-growth, both are required but it is a much easier solution. So, what you have is the reflector is a Bragg reflector here. In this section, we have Bragg reflector. Bragg comes, Bragg means periodic (()) (44:35).

So, there is a periodic structure which is providing reflection and that periodic structure is wavelength selective and therefore you have distributed Bragg reflectors. So, these are the Bragg reflectors at the 2 ends. The gain providing contact electrode is only here. The current is flowing through this region. Current is not flowing through this region. This is the structure of DBR laser. What are the advantages over DFB. A DBR laser is much more stable in frequency.

I am making a statement that a DBR laser is much for stable in frequency of the output. In the case of a DFB laser, alright. Let me go back to the DFB here. You see that the metal contact is here, carriers are flowing across. Carriers are also flowing through the grating region. Carriers are flowing through the grating region which is selecting the frequency. We have an expression that lambda B hear, that is the frequency which is selected = 2n effective into lambda.

Lambda is fixed because once you have fabricated the corrugation that is it, lambda is fixed. However, the refractive index of the medium here is a function of the current which is flowing through. When carriers are injected, the medium becomes as gain or loss depending on injection of the current. Depending on injection of current, we can make either EFC-EFV > EG or < EG. If it is > EG, then only we have gain.

So, what determines, the injection current determines whether there is gain or not. Refractive index of a medium in general is given by nr-i*ni. Refractive index of the medium in general is complex and because it is the complex part which will tell you whether the medium is absorbing or amplifying. If ni is > 0 here, this means it is absorbing. If ni is < 0, it is amplify.

This is basic optics, I hope you understand that psi can be written as (()) (48:05) plane wave, e to the power of ikx, that is ikz, if it is propagating in the z direction into i omega t, Az-omega t or omega t-kz whatever way that you want. So, you see that k here is k0*refractive index n which is = k0 into this refractive index is a real part-i*ni part and therefore you have this term here. If you look at this term you get e to the power i k 0 nr*e to the power the second part, that is minus i square.

Let me write this in the other way because normally in optical waveguide in quantum mechanics, we write this way but in optical waveguide we write i omega t-kz, so k*z and this is here. So, the first part is minus i k n 0*r, this is an oscillatory part. The second one will be minus i*minus i, so minus minus plus and i square is minus one, so you have –k0*ni*z. What I have written is an expression for plane wave. This is propagating plane wave in the z direction, okay. So, i = amplitude into this.

If the refractive index is complex, so k is k0*n, refractive index is complex. I have substituted here the complex quantity. Then, I just substituted back, i omega t have left, you can keep i omega t. So, A*e to the power of i omega t here. So you see that there is a term which is coming like this. This is exponentially decaying. These are oscillatory. So, if you want to see the intensity which is = mode psi square which is equal A square into these 2 terms are gone and you have e to the power minus 2k0ni*z.

So, what does that mean, the intensity is decaying with z. The power is decaying with z, that means if ni is positive then this is absorbing with z. The medium is absorbing, are you able to follow, that this z here, therefore as z increases, this quantity is exponential e to the power of minus something which means 1/e to the power, so it is > 1 in the denominator, so this quantity drops down continuously.

This A square I can write as I of z = I0*e to the -2k0ni*z. The intensity is continuously decreasing with z if ni is > 0, that is what I have written here. ni is > 0 means the medium is absorbing. If ni is < 0, if you substitute ni as negative, negative, negative becomes positive, so it is amplifying, medium is amplifying. When you pass a current here, the refractive index is this.

When you pass a current, ni decreases and it goes from greater that 0 to < 0 and that corresponds to gain. By passing an injection current and maintaining the gain in the medium means ni has become less (()) (52:21). The medium is complex in general and amplifying and absorbing media are complex in general, have a complex refractive index. Normally, we do not consider this because we treat media with a transparent.

If you take glass and do all the optics, then you consider that the glass is transparent. You are not considering absorption that is why you never use this part. Transparent means this is = 0, ni = 0 is transparent. So, we only talk about the real part of the refractive index in normal optics but if the medium is absorbing or amplifying, it means the refractive index is complex. So, we come to the point here. As you pass current, ni changes in the medium.

Ni goes from positive to negative, that is the medium becomes absorbing, then transparent at transparency carrier density and then it become amplifying which means ni is changing. Through Kramers-Kronig relation, it relates the imaginary part to the real part of the refractive index. This is true for any complex quantity of a real system that the imaginary part of the complex number is related to the real part of the complex number. So, if this changes, this changes through this relation. They are linked through this relation.

If this changes, the frequency changes because you see this. This was the real refractive index, so this changes if the real part of the refractive index changes, the frequency changes and therefore depending on the current here, if you have a larger current or smaller current, the frequency of the light gets shifted in the case of a DFB laser where in the case of a DFB laser here. This is the DFB laser. The current is passing through the grating which is selecting the frequency.

Because the refractive index of the medium here changes due to injection current, the frequency also changes with injection current in a DFB. In a DBR, here is the DBR structure, the current is passing through the active medium where there is no frequency selection. Frequency selection is done at the ends and therefore that is not affected. The refractive index here is not affected because the carriers are moving here and therefore the frequency remains stable.

Irrespective of the current, the frequency remains stable. This is the main advantage of a DBR laser over a DFB laser. However, it is a little bit more difficult to fabricate at the ends and normally unless you really have an application where you require extreme high stability of the laser frequency tend to use DFB lasers. Therefore, in communication, we normally use DFB lasers because we use the current system at least use the on off key or intensity modulation scheme and therefore it is not an issue.

However, if you use coherent system, then this will become an issue. The frequency shift will be an issue, okay. We will stop this time here. So, we will stop here and continue in the next class.